

AIR WAR COLLEGE

AIR UNIVERSITY

DIRECTED ENERGY WEAPON SYSTEM
FOR
BALLISTIC MISSILE DEFENSE

by

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A Research Report Submitted to the Faculty

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BIOGRAPHY

Lieutenant Colonel David M. Mason entered the Air Force in 1989 as a graduate of North Carolina Agricultural and Technical State University in Greensboro N.C. Over the course of his career, Colonel Mason garnered a variety of weapon system expertise during several key space and missile operational assignments. He has over ten years in nuclear-related billets to include Minuteman III ICBM combat crew commander, flight commander, and squadron commander. As commander of the 490th Missile Squadron at Malmstrom Air Force Base in Great Falls, Montana, Colonel Mason was responsible for the daily oversight and operational mission requirements of five missile alert facilities and 50 intercontinental ballistic missiles. Colonel Mason has also served in a variety of key staff assignments which include, speechwriter to the AETC commander, Space and Missile Assignments Officer, and Division Chief of the Air Force's Nuclear Operations Directorate located at the Pentagon. While there, he was responsible for the policy and planning guidance for the service's \$13 billion dollar nuclear enterprise.

Colonel Mason earned a Bachelor of Science Degree from North Carolina Agricultural and Technical State University, a Masters of Management Degree from Lesley University, and a Masters of Strategic Studies Degree from the Air War College.

PREFACE AND ACKNOWLEDGEMENTS

In 2008, I had the privilege of participating in a major study effort conducted by the Air Force's Center of Strategy and Technology. This organization was charged with conducting a 25-year study and engaging in long-term strategic thinking about technology and its implications to the future of U.S. national security. Under the leadership of Colonel John P. Geis, Director of the Center, I was afforded the opportunity to interact with some of the most brilliant, strategic thinkers in the Air Force. These professionals introduced me to some important directed energy weapon systems and support system design concepts that re-define how the U.S. conducts missile defense operations.

This research paper is an outgrowth of engagements directed energy technology experts. I became interested in this technology during the early phase of the school year and devoted most of the remaining part of my Air War College experience toward researching high energy lasers and how they could be applied to battlefields of the future. I'm very appreciative of the support provided by Colonel Geis as well as Colonel (Retired) Ted Hailes. These two leaders helped me formulate my research idea into a structured and well-designed professional studies paper.

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CHAPTER 1 -- INTRODUCTION

“America must build effective missile defenses, based on the best available options, at the earliest possible date. Our missile defense must be designed to protect all 50 states, friends and allies from missile attacks by rogue nations or accidental launches.”

President Bush

Ballistic missiles carrying nuclear weapons and the proliferation of nuclear weapons and related technologies represent two of the gravest threats to the security of the United States and its service members deployed overseas. The threat environment the U.S. will be confronted with will be fundamentally different from the Cold War period and the period characterized by today's global fight against terrorism. The international environment shaped by rogue states, the withdrawal of Cold War-era security guarantees, and concerns about the availability of advanced weapons to terrorist organizations ensure that the growing ballistic missile threat environment and the proliferation of nuclear weapons remain central to U.S. security concerns.¹

The list of international actors who either possess ballistic missiles or seek to procure this technology has grown exponentially over the years.² Take for instance, in 1972; just nine countries had a ballistic missile arsenal.³ Today, that number has grown to 33 countries which include hostile regimes with ties to terrorist organizations.⁴ Rogue states, chief among them North Korea and Iran, have placed a premium on the acquisition of nuclear weapons and ballistic missiles of increasing range.⁵ Syria possesses one of the largest ballistic missile force structures in the Middle East and has an active program conducting research and development of nuclear technologies.⁶ Both India and Pakistan have active nuclear programs and North Korea confirmed its position in the world as a nuclear-capable state after detonating a 1-kiloton weapon in 2006.⁷

Both Russia and China continue to expand the range and sophistication of their strategic weapons arsenals.⁸ While Russia maintains the world's second largest nuclear stockpile, China is increasing its nuclear weapons capacity and also maintains the world's most active ballistic missile production program. Of equal concern is China's propensity to proliferate WMD and ballistic missile technology or materials.⁹ In 2007, the U.S. imposed sanctions on several Chinese companies for sales of WMD and missile technologies.¹⁰ However, Beijing continues to fall short in its enforcement of export controls in response to the sanctions which in-turn empowers private Chinese businesses to continue selling technologies to rogue states like North Korea and Iran.¹¹

Terrorist organizations, in particular, al-Qa'ida, remain interested in acquiring WMD and delivery systems for use in attacks against the U.S. and its service members deployed overseas.¹² One of the more disturbing scenarios examined within the intelligence community highlights how terrorist organizations could launch a short-range ballistic missile attack from ships parked a short distance from America's coastline.¹³ An action of this nature could produce mass casualties, economic disruption, and localized terror on a large scale.

The growth of ballistic missile platforms and the sophistication of these systems are evolving at a pace that no longer allows the luxury of long lead times for defensive counter-measures.¹⁴ In order to address this complex and increasingly growing danger, the U.S. must move beyond the initial missile defense deployment stages of recent years and focus on deploying a system capable of providing comprehensive protection of America's homeland.¹⁵ This defensive network must also be able to dissuade would-be missile possessors from costly investments in missile technologies, and to deter future adversaries from confronting the United States with ballistic missiles carrying WMD.¹⁶ Additionally, America's strategic objective

should make it impossible for any adversary to influence U.S. decision-making in times of conflict through the use of missile platforms or WMD blackmail.¹⁷

These priorities necessitate the deployment of a system capable of constant defense against a wide range of missiles in all phases of flight: boost, midcourse, and terminal.¹⁸ A multi-layered system, encompassing extended-range conus and theater-based defense assets would provide multiple opportunities to destroy incoming missiles originating from any point around the world.¹⁹ However, a truly global capability cannot be achieved without incorporating interdiction capabilities through space as one of its key operational enablers.²⁰ In the twenty-first century, space has replaced the seas as the ultimate frontier for commerce, technology, and national security. Interdiction capabilities navigating through space affords maximum opportunities for missile interception on a global scale. As directed energy technology continues to mature, lasers could one day provide a viable interdiction capability through space to defend the U.S. against the growing threat of missile attack.

Two directed energy weapon systems that could provide this network are the free-electron laser and the space-based relay mirror. Although still early in the technological development stages, these two systems hold great promise for creating a robust, defense network capable of extended-range operations. This network would provide the final layer to America's quest of developing a multi-layered defense infrastructure while also covering for any limitations posed by today's kinetic energy intercept technology.

The currently deployed kinetic-kill missile defense system is limited to mid-course defense and effective against only a few missiles with simple decoys. Free-electron lasers complimented by space-based relay mirrors would deter adversaries from launching an attack against the U.S.

and service members since defensive engagement would be near-instantaneous. Should deterrence fail, this network would autonomously employ high energy lasers to defeat any target regardless of location of origin. When combined with a kinetic-kill infrastructure, the free electron laser and space-based relay mirror could provide the U.S. with a responsive network of options. There is great promise on the horizon for both the free-electron laser and space-based relay mirror to become the next generation of missile defense and re-define how the U.S. conducts operations to secure the homeland against air-based threats.

The purpose of this research paper is threefold. First, the paper will look at three potential adversaries of the U.S. who may become capable of endangering America's security with the use of ballistic missiles. From these examples, it will be clear that a change to the current missile defense force structure is needed. Next, this thesis will examine the growth of ballistic missile technology and offer how a free-electron laser weapon system coupled with a dedicated network of space-based relay mirrors could provide the U.S. with an enduring capability to defeat missile threats on a global scale. The successes of the Airborne Laser may offer the blueprint for developing a land-based free-electron laser missile defense architecture. I will conclude this research paper by offering a Concept of Operations that can be used by the Air Force institution to continue developing and eventually procuring a directed energy weapon system. Make no mistake about it, procurement of this system will be time consuming, technically challenging and expensive, but it is a necessary exercise in protecting the U.S. from growing threats. A conus-based free-electron weapon system, coupled with a dedicated network of space-based relay mirrors could provide the U.S. with a viable and credible missile defense capability.

CHAPTER 2 – FUTURE BALLISTIC MISSILE THREAT ENVIRONMENT

The environments outlined below are illustrative in nature and gathered from unclassified intelligence estimates and open-source periodicals. The purpose of the scenarios are to highlight the growing ballistic missile threat posed by three potential adversaries the U.S. could be confronted with in the future ... China, Iran, and North Korea. Some intelligence experts predict the future security of the U.S. will reach a culminating point when rogue states and irrational actors are able to acquire nuclear weapons and the means to deliver them. This bleak outlook could hold major U.S. population centers and service members deployed overseas at great risk. Although not classified as a rogue state, China already possesses a sophisticated weapons arsenal that could hold any location within the U.S. at risk. Intelligence networks have reported that North Korea and Iran conduct business with China which has been useful to expediting their ballistic missile and nuclear weapons development program.

The information below may be disturbing as it highlights how potential adversaries will continue advancing missile technologies and nuclear weapons production which could challenge U.S. national security interests. The information uses real places, real technologies and real people, in some instances, throughout.

CHINA

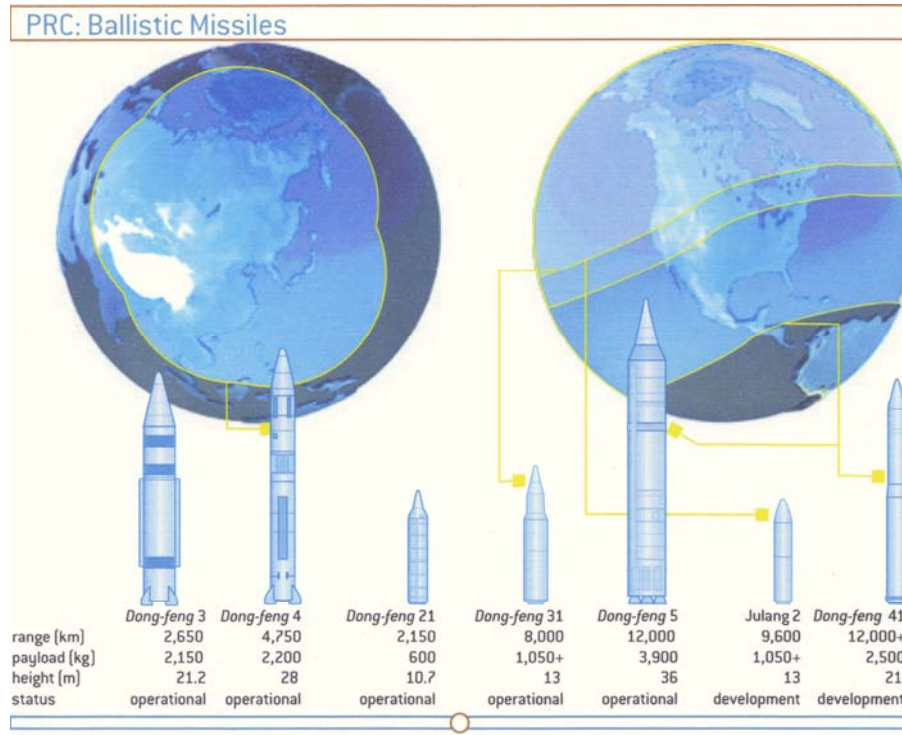


Figure 1 Courtesy of 2009 Independent Working Group, Missile Defense, the Space Relationship, and the Twenty-First Century

While not yet an avowed peer competitor of the U.S., China is involved in an intense competition with America for power and influence in both the region and on a global scale. The country's regional and global power ambitions are enabled by a robust military capability that includes a wide-range of ballistic missiles. According to Defense Department intelligence sources, China has the most active ballistic missile program in the world.²¹ It is developing and testing offensive rockets, forming additional missile units, qualitatively upgrading certain missile systems, and developing methods to counter missile threats.²² China's missile modernization efforts build upon current capabilities that encompass ballistic missiles able to target the U.S. as well as Japan and other regional allies.²³ For example, China has over 46 Dong-feng 4, Dong-

feng 5, and Dong-feng 31 intercontinental ballistic missiles, approximately 35 intermediate-range platforms, and hundreds of short-range rockets currently deployed.²⁴ Between 990 and 1074 short-range rockets are deployed opposite Taiwan and that number increases by 100 each year.²⁵ At the same time, China is in the midst of a massive, multi-year strategic military modernization effort which includes upgrading its weapons platform arsenal.

Modernization efforts include deploying the Deng-feng 31 ICBMs with multiple independently re-targetable re-entry vehicles. This design would enable the warheads to defeat the currently U.S. deployed kinetic energy missile defense systems. Additionally, Beijing is placing a lot of emphasis on developing a solid-fuel “launch on demand” system designed to transform its strategic offensive nuclear forces from large stationary missiles to more versatile road and rail mobile variants.²⁶ Notably, China has developed a new submarine-launched version of the Deng-feng 31, the Julang 2. This platform is capable of traveling 9,600 kilometers and according to U.S. defense estimates, will enable Chinese submarines to hold major areas of the U.S. at risk while still located in port.²⁷ This capability is even more frightening considering the remarks made by Chinese General Zhu Chenghy who stated that “nuclear weapons would have to be used if the United States intervened militarily in a conflict over Taiwan.”²⁸

The Sino-American diplomatic relationship represents one of the greatest uncertainties of the twenty-first century.²⁹ National financial experts and the World Bank Organization agree that China will have the world’s top ranked economy by the year 2035 in terms of its gross domestic product. If that GDP translated directly into military power, then by the year 2030, China would have the capacity to afford military forces equal to or far superior to current U.S. capabilities.³⁰ While this prediction must be tempered with calculations such as per capita measurements, even by conservative measures, it is likely that by the year 2030, China will

modernize its forces to reach a level of approximately one quarter of current U.S. capabilities without any significant impacts on the economy.³¹ Regardless of the U.S. approach to China whether containment or engagement, or a combination of both, the fact remains China will become increasingly important in the considerations and strategic perceptions of America's civilian and top military leaders.

The course that this communist state takes, in terms of their growing economic strength and military development, will determine much about the character and nature of the twenty-first century remains to be seen. Whether it will be a bloody century or one of peaceful global co-existence between the U.S. and China. At this point, the Chinese are uncertain about these future prospects but what does appear to be relatively clear is Sino leaders are thinking about potential long-term conflicts with the U.S. and are aggressively working to bolster their strategic weapons arsenal.

IRAN

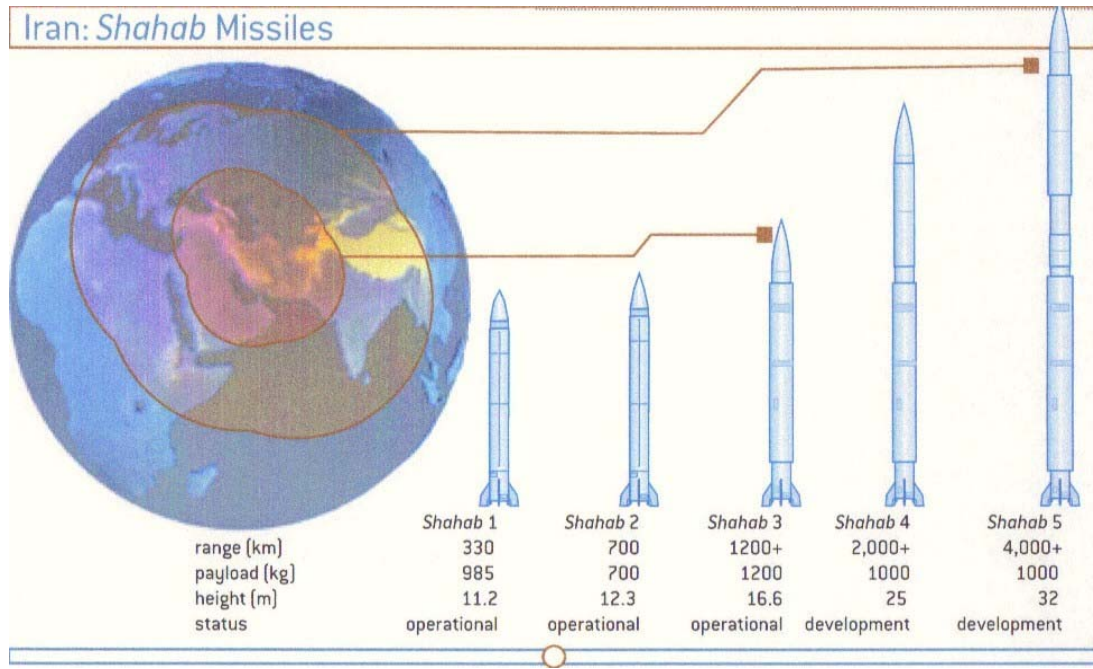


Figure 2 Courtesy of 2009 Independent Working Group, Missile Defense, the Space Relationship, and the Twenty-First Century

With the benefit of assistance from abroad, including North Korea and Pakistan, the Islamic Republic of Iran has moved forward with its ballistic missile program.³² Although Iran has been ballistic missile-capable since the 1980s, the year 2003 marked a major milestone in weapons platform technology. Iran was able to operationally deploy a 1,300 kilometer-range Shahab 3, which is now capable of targeting Israel and Turkey as well as U.S. service members deployed in the Persian Gulf region.³³ Since then, Iran has begun mass producing the Shahab-3 missile as well as working on a number of Shahab variants.³⁴ This effort has yielded several important dividends.

In September 2007, Iran publicly unveiled a new medium-range missile, the Ghadr-1, at a military parade in Tehran.³⁵ This platform, which Iran claims has a range of 1,800 kilometers, appears to be an extended-range variant of the Shahab-3.³⁶ Subsequently, in November 2007, Iran carried out a test of the Ashoura rocket which is a 2,000 kilometer-range solid fuel variant of the Shahab. These tests are further evidence that the Republic is trying to increase the range of its ballistic missile arsenal with the goal of developing an intercontinental system by the year 2015.³⁷

This effort is closely linked to the Republic's interest in developing nuclear weapons. Iran was known to be reviving its civilian nuclear program since the 1990s, but revelations in 2002 and 2003 of clandestine research into fuel enrichment and conversion raised international concern that Iran's interest had moved beyond a peaceful intent.³⁸ Despite the insistence that nuclear technology is being looked at for peaceful purposes, many leaders within the international community remain skeptical of Iran's true intentions. And, despite a U.S. intelligence finding in November 2007 that concluded the Republic halted its nuclear weapons program in 2003, U.S. officials continue to warn that Iran seeks to weaponize its nuclear program.³⁹

Since December 2007, Iran has built a stockpile of low-enriched uranium hexafluoride.⁴⁰ According to the International Atomic Energy Agency, the country's stockpile had reached more than 1,000 pounds by August 2008 with monthly production rates of more than 100 pounds.⁴¹ If production rates continue at this pace, Iran should be able to produce 15,000 pounds of uranium before the close of 2009. This uranium could be re-circulated through its centrifuges to produce the 35 pounds of weapons grade uranium which is sufficient for one bomb.⁴² In April 2008, Iranian President Mahmoud Ahmadinejad disclosed that his government had begun to install

another 6,000 centrifuges at the Natanz facility.⁴³ Ahmadinejad also announced to supporters at that time that, “Iran’s victory in this biggest political battle will lead to new international developments.” Thus all indicators point towards a nuclear-capable Iran as early as 2010.⁴⁴

NORTH KOREA

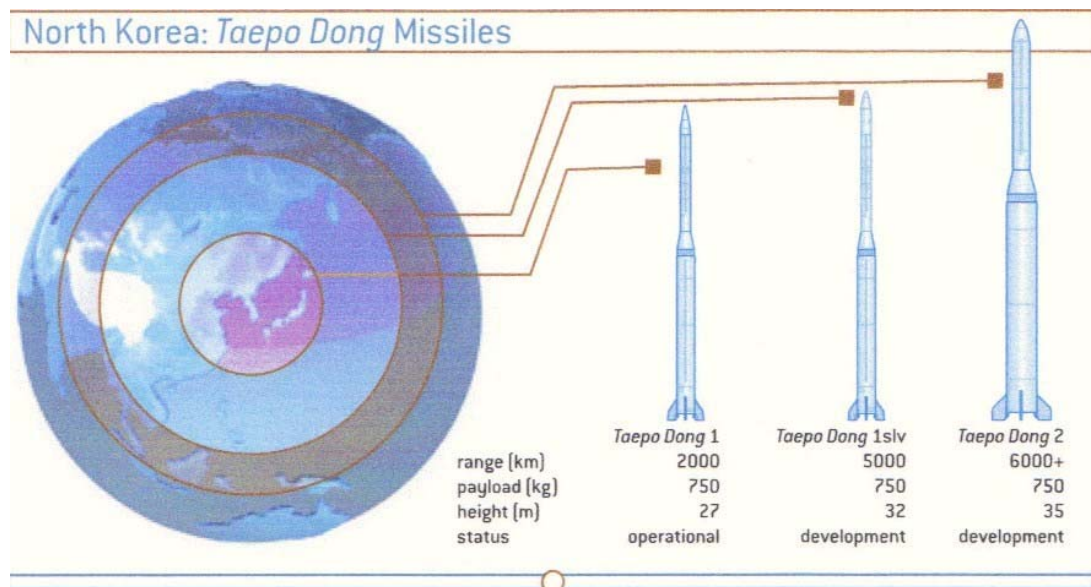


Figure 3 Courtesy of 2009 Independent Working Group, *Missile Defense, the Space Relationship, and the Twenty-First Century*

North Korea is the most advanced of the “small state” missile developers and since the demise of the Soviet Union, has probably the largest missile arsenal in the developing world. Pyongyang has engaged in extensive efforts to conceal the size and scope of its missile programs, though estimates suggest that it may have deployed as many as 1000 rockets.⁴⁵ This number includes 600 to 800 scud-type short-range rockets, 150 to 200 medium-range platforms, and 50 long-range assets.⁴⁶

In July 2006, North Korea launched seven ballistic missiles, including the new long-range Taepo Dong 2 rocket, as part of a series of test launches.⁴⁷ While the Taepo Dong missile failed, it signified a considerable advance in the development of Pyongyang's extended range missile capability.⁴⁸ The Congressional Research Service has indicated that the Taepo Dong's design would allow it to deliver a 1,500-kilogram warhead to targets as far away as 8,000 kilometers.⁴⁹

Additionally, North Korea has been nuclear capable since 2006. In 2008, North Korean officials admitted that 37 kilograms of plutonium had been produced at the Yongbyon reactor, which was enough for nine nuclear weapons.⁵⁰ American assessments suggest that the actual amount of plutonium produced was likely much higher and that as much as 60 kilograms could have been extracted.⁵¹ Based upon this judgment, North Korea may have as many as 15 nuclear weapons, though most estimates within the U.S. intelligence community place the number at around ten.⁵²

In 2006, North Korea successfully conducted an underground low-yield nuclear test. This test however did not produce a significant nuclear yield with some estimates being as low as one kiloton. After the test, Pyongyang re-engaged in the Six Party Talks which was aimed at ending its nuclear development program. In response, the U.S. moved toward lifting some of the sanctions imposed against this rogue state and also removing the country from the list of nations that sponsor terrorism. However, in December 2008, North Korea once again withdrew from the Six Party Talks and agreed to only rejoin if Japan were removed from discussions.

It remains to be seen whether Pyongyang will re-engage in a diplomatic solution and end continued nuclear weapons production. With the current withdrawal from talks, defense industry experts and national intelligence centers have concluded it's only a matter of time before Korea resumes long-range missile development and possible employment with a capability to transport WMD payloads.

CHAPTER 3 – DIRECTED ENERGY WEAPON SYSTEM

Directed energy weapons have come of age over the years and could be scaled to weapons grade power to defend against the growing threat of ballistic missiles.⁵³ The idea of a “death ray” which can instantly engage a target from great distances has retained its allure over the years since H.G. Wells published “War of the Worlds” in 1898.⁵⁴ Although it is plausible to believe weapons platforms capable of attacking a target at the speed of light would only happen in science fiction movies, the fact is, near instantaneous applications and global-range capabilities are two core characteristics that make directed energy so attractive to defense experts and industry leaders. Directed energy systems can take the form of lasers, high-power microwaves, and particle beams, but for the purposes of this research paper, the focus will remain solely on lasers.

Directed energy lasers are produced by a number of different methods, ranging from rods of chemically laced glass, to energetic chemical reactions, to the wiggling of free electrons. Beams can either be continuous or short-pulsed and all produce intense levels of energy in every wavelength of the electromagnetic spectrum, from infrared to ultraviolet. Laser beams are capable of destroying targets from great distances which make the technology a prime candidate for continued research and development.

Lasers represent the most mature form of directed energy. The power output necessary for a laser to reach weapons grade power for ballistic missile defense is a minimum of 1 megawatt (1000 kilowatts).⁵⁵ Compared with conventional weapons, which rely on the kinetic or chemical energy of an intercept vehicle, lasers can hit a target with sub-atomic particles or electromagnetic waves.⁵⁶

During the past two decades, this technology has advanced considerably in areas such as power, beam control, and pointing and tracking techniques which enables the system to hit a target at great ranges.⁵⁷ This energy can be used to engage satellites, aircraft, and vehicles, but the most promising aspect of this technology is the ability to destroy missiles traveling at mach or supersonic speeds. In addition to being able to engage rapidly moving targets, lasers can be re-directed by mirrors to hit these targets that fall outside of line-of-sight range. This all can be done without compromising much of the beam's initial power.⁵⁸ The unique attributes of lasers has the potential to revolutionize missile defense operations. Those attributes include:

1. Speed of Light Capability: This represents a core significant advantage of lasers. With the potential to travel at 186,000 miles per second, directed energy offers the warfighter near-instantaneous options to destroy targets at great distances. Quite naturally, this attribute also greatly simplifies tracking and targeting of missiles while also greatly reducing target counter-measure techniques.
2. Precise and Adjustable Targeting: Directed energy offers extremely precise targeting effects, which are capable of delivering energy to a small spot on a missile. This phenomenon would cause a missile to undergo aerodynamic stress which would lead to catastrophic failure. A related feature of this characteristic is the ability to adjust the amount of energy required to successfully propagate through the atmosphere from surface locations. The free-electron laser is the only form of directed energy that has demonstrated that capability.
3. Affordability: Once deployed, lasers will be able to intercept missiles at relatively low costs per shot. Although the beam-generating system may be initially expensive to build and

maintain, the price per engagement will be relatively cheap as compared to conventional systems.⁵⁹ For example, the Missile Defense Agency conducted a missile intercept experiment back in December of 2008 using a kinetic energy intercept vehicle. The total cost of the experiment ranged between \$120 million and \$150 million, although the Agency did employ several other defense systems to ensure a successful intercept.⁶⁰ Navy surveillance ships and space-based command and control platforms provided a robust network for the experiment that assisted with launch intercept. .

4. Repetitive Engagements: Lasers have a great capacity for continuous engagements over an extended period of time, and are constrained only by the availability of power and the need to vent energy producing by-products such as heat. Conventional weapons, especially those firing precision-guided munitions, are constrained in the number of engagements it can execute. In addition to engaging threats, lasers can be used to detect, image, track, and illuminate targets. This process can work autonomously with the “kill laser” while also enabling the platform to lock onto a multiple number of missiles.
5. Weapon System Diversity: Directed energy systems can be placed on a variety of platforms to achieve optimum results. Airborne lasers are capable of attacking targets out to several hundred kilometers, while a ground-based platform could attack targets on a global scale. A complimentary network of space-based relay mirrors is required to extend a ground-based system to a global scale.

The Airborne Laser – the Air Force’s High Energy Missile Defense System



Figure 4 Courtesy of Boeing Industry

After more than 40 years of technology development and billions of dollars in investments, the Department of Defense is on the verge of deploying its first airborne, high-energy weapon system.⁶¹ The Airborne Laser (ABL), which is being developed by the U.S. Missile Defense Agency; and the industry team of Boeing, Northrop Grumman, and Lockheed Martin, will provide a rapidly deployable, precise, speed-of-light capability to destroy ballistic missiles during the boost phase of flight.⁶² Its revolutionary use of directed energy makes it unique among the United States’ airborne weapon systems, with the potential to attack multiple targets at the speed of light with a range of hundreds of kilometers.⁶³

The mission of the ABL is to detect, track, target, and destroy all classes of ballistic missiles.⁶⁴ The weapon system uses two solid state lasers and a megawatt-class Chemical Oxygen Iodine Laser (COIL) housed onboard a modified Boeing 747-400 freighter aircraft to destroy missiles. Six infrared sensors positioned on the outside of the aircraft enable the platform to scan the horizon for threats.⁶⁵ Once a threat has been detected, two kilo-watt solid state lasers lock on to the target and provide the beam director a precise aiming point as well as pre-conditioning the weapon system to account for atmospheric abnormalities.⁶⁶ Finally, the ABL will then fire its high energy COIL from a turret located in the nose of the aircraft to destroy a target.⁶⁷ The system is also designed to perform as an intelligence, surveillance, and reconnaissance platform.⁶⁸ This feature of the weapon system is designed to collect and pass information on launch sites, target sites, and predicted impact points to other elements of a missile defense network.

The kill mechanism on the aircraft, the COIL, combines a mixture of hydrogen peroxide, potassium hydroxide, chlorine gas, and water to generate its lethal beam. The aircraft's beam control and fire control system maintain the strength and direction of the laser as it travels through the atmosphere.⁶⁹ The beam travels at the speed of light until it reaches the target and then heats the missile's metal skin until it cracks. Since the interior of the booster is pressurized, the crack in the skin will cause fuel to explode, which will disintegrate the threat over its launch site.

The Airborne Laser weapons system recently completed the final stages of ground-based system testing. In December 2008, the Missile Defense Agency along with defense industry contractor, Boeing, fired the high energy COIL through a beam control and fire control system for the first time since the platform has been undergoing testing.⁷⁰ The beam then excited the aircraft and was captured by a Range Simulator Diagnostic System, which provided simulated targets as well as "dump" and diagnostics for the laser beam.⁷¹ The analysis of the test indicated the weapon system scored a direct hit.

Today, the Airborne Laser is preparing for final system checkout and initial operational certification. This methodical process is necessary to certify all onboard components of the weapon system and ensure the system's high-energy COIL continues to work autonomously with the solid state lasers. Final system checkout will culminate with a live in-flight missile-shoot-down demonstration during the summer of 2009.⁷² If the test succeeds, plans are to build another six ABL-armed 747s and deploy the assets to theaters of interest.

Advantages of Airborne Laser Weapon System

Fielding the laser will provide the U.S. and its allies with a mobile high altitude weapon system that can take multiple shots at rapidly accelerating ballistic missiles that have thousands of pounds of explosives or weapons of mass destruction.⁷³ Within a second, a directed energy laser beam can engage the outer protective skin of the missile and disrupt the flight path of the threat.⁷⁴

Since the system entered testing, the laser has succeeded through numerous technical and engineering challenges. Scientists had to ensure that the physics of the chemical and solid state laser worked autonomously in the small confines of the aircraft. The system has met all of its critical operational checkpoints and has fired the laser on more than 70 occasions.⁷⁵ And once the laser becomes operational, it will compliment other ballistic missile networks including the Ground-Based Midcourse Defense System and the Aegis Ballistic Missile Defense System.⁷⁶ With so much at stake during a missile attack, the Missile Defense Agency is deploying a range of capabilities to target threats in the boost, mid-course, and final stages of flight to provide a maximum level of protection for the U.S. and its allies.

Limitations of the Airborne Laser

The Airborne Laser was designed to be used against tactical ballistic missiles and may have limited viability against adversaries who rely more on intercontinental ballistic missiles located well within their borders. The 200 nautical mile range of the system may become problematic against silos and launch pads that are at a considerable distance from a nation's borders.⁷⁷ Additionally, due to flight escort requirements, the laser would not have continuous presence over a region of interest. To get into a position to engage a target, the aircraft would

require long flights which may keep the aircraft over hostile territory for extended periods of time. This makes the employment of the laser only applicable to certain theaters of interest. Although the future of the defensive platform is quite promising, the range of this network will be limited to line-of-sight defensive operations. A system that could potentially provide an extended-range option for missile defense is a ground-based directed energy weapon system. Coupled with space-based relay mirrors, this network would be capable of destroying targets on a global scale during their boost phase of flight. This deployment of next-generation directed energy technology would represent the final step in providing the U.S. with a multi-layered missile defense network.

Free-Electron Laser

For decades, scientists have been slowly working on a laser that could potentially have an unlimited power supply and could be tuned to effectively penetrate the air, at just the right wavelength.⁷⁸ And for many years, all they could generate was a laser only able to achieve light bulb strength.⁷⁹ Finally, in 2004, scientists at the Thomas Jefferson National Accelerator Facility finally managed to assemble a free-electron laser (FEL) that could generate 10,000 watts of power.⁸⁰ Now researchers have started on an effort to build a system that can generate 100 kilowatts of power which is considered the minimum threshold for weapons grade power.

Free-electron lasers represent the latest advancements in directed energy technology. The laser shares the same optical properties as the conventional lasers such as emitting a beam of coherent electromagnetic radiation which can reach high power, but which uses some very different operating principles to form the beam.⁸¹ While a conventional laser uses bound atomic or molecular states as its lasing medium, an FEL uses electrons fed from an electron accelerator to generate energy. This gives the electrons the widest frequency range of any laser type, and makes the beam distinctly tunable.⁸² FEL beams have the capacity to operate in wavelengths from the infrared to the ultraviolet which is unachievable by most conventional lasers.

To create an FEL, a beam of electrons is accelerated to relativistic speeds.⁸³ When the electrons enter into a magnetic field, which is located in the undulator, the field “wiggles” them up and down, which causes the electrons to emit photons.⁸⁴ As the electrons oscillate up and down, they radiate in a forward direction which causes the wavelengths of light to become shorter.⁸⁵ Since the energy of an emitted photon depends upon the electron velocity and

magnetic field strength, the frequency and color of the wavelength can be controlled. [Reference diagram below for pictorial explanation of laser operations].

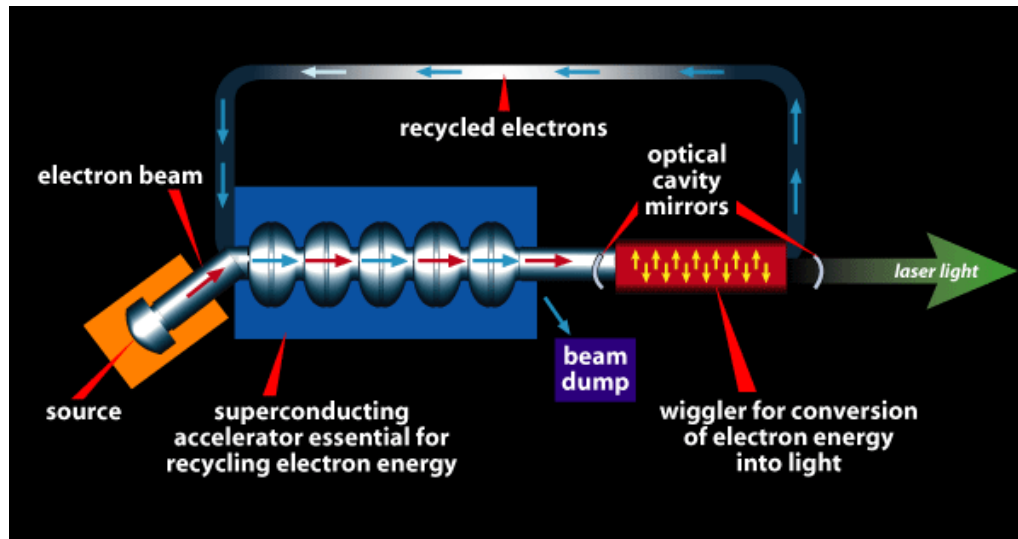


Figure 5
Courtesy of Thomas Jefferson Laboratory

“The FEL is based on something called an energy recovered linac which is illustrated above. Electrons are released from the source at the lower left, and are accelerated in a superconducting linear accelerator (linac). After emerging from this linac, the electrons pass into a laser cavity which has a wiggler at its center. This wiggler causes the electrons to oscillate and emit light which is captured in the cavity, and used to induce new electrons to emit even more light. After exiting the optical cavity the electrons then travel around the loop at the top and back into the linac. Here they give up most of their energy to a new batch of electrons, making the process highly efficient.”⁸⁶

The sequence that generates the end product, which is the laser beam, is the phase in which the electrons are being emitted. Since the intensity of light is directly proportional to the field of electrons being emitted, this has a proportional effect on the beam. Like other high-energy laser systems, the FEL has the potential to offer extremely fast tracking and response times for engaging fast-moving ballistic targets.

The speed-of-light delivery timeline of a FEL has generated great interest from the Navy for ship-based defense. FELs offer the service a capability to protect ships against cruise

missiles that are not defensible by conventional lasers because of the moist operating environment.⁸⁷

Starting in the late 1960s, the Navy embarked on a significant high-energy laser development program, looking first at gas dynamic carbon dioxide lasers and then deuterium fluoride chemical lasers.⁸⁸ Although the service experienced some success with these lasers, they decided to cancel further research and development efforts because of propagation issues caused by thermal blooming. It wasn't until the FEL experienced improvements in scalability to higher energy levels did the Navy reinvigorate its interest in laser ship-based defense.

In October of 2006, Thomas Jefferson Laboratory set a new record by producing a 14.2 kilowatts of laser beam power at an infrared wavelength of 1.61 microns or 2 millionths of a meter.⁸⁹ The best performance for a laser traveling through the earth's atmosphere is found in the near infrared and visible wavelengths.⁹⁰

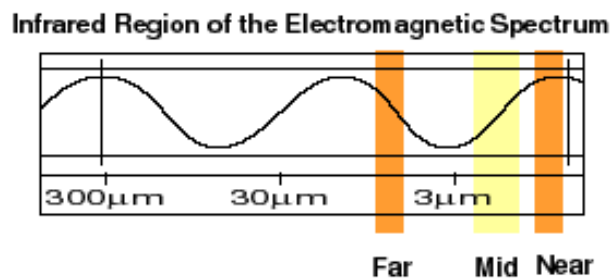


Figure 6 Courtesy of Thomas Jefferson Laboratory

"Infrared light has a range of wavelengths, just like visible light has visible wavelengths that range from red light to violet. "Near infrared" light is closest in wavelength to visible light and "far infrared" is closer to the microwave region of the electromagnetic spectrum. The longer, far infrared wavelengths, are about the size of a pin head and the shorter, near infrared ones are the size of cells, or are microscopic."⁹¹

These colors allow the beam to be focused at sufficiently long ranges to engage distant targets, yet avoid excessive losses due to scattering, absorption, multi-photon ionization, and catastrophic beam absorption.⁹²

In 2008, the Navy issued a Broad Agency Announcement to design and fabricate a 100 kilowatt FEL for the purposes of developing a weapons grade, high energy weapon system. Although the FEL is seen as a possible way for the Navy to achieve megawatt-class power levels, there remains much work to be done before the system can be scaled to 100 kilowatts.

Scientists don't anticipate reaching weapons grade power for another several years. Two major system limitations that may slow progress are halo and waste dissipation effects. The heat dissipation limitation applies to parts in and around the wiggler or undulator.⁹³ Among the scientists at the Directed Energy Conference in Hawaii in November 2008, there was considerable concern that as the power of a FEL system increases, excess heat may affect the magnetic properties of the wiggler or undulator which may become heated beyond their Currie Point (point at which the wiggler or undulator lose their magnetic properties).⁹⁴

As for "halo effect" this phenomenon occurs when a large number of stray electrons hit the walls of the confinement chamber and causes the system to become radioactive during operation. This could cause catastrophic failure of the laser.⁹⁵ With this limitation, even fractions of a millimeter in system alignment could result in radically different beam alignment causing unintended effects.⁹⁶ Ruggedizing these systems to be viable for missile defense application may be challenging but the future promise of minimizing the effects of haloing and heat dissipation looks promising.

Advantages of FELs over Conventional Lasers

Trade-offs between competing laser technologies provide the basis for deciding if the FEL is the appropriate directed energy source for missile defense operations. If a FEL is to be deployed, it must showcase clear advantages over other laser concepts. Considering the Airborne laser will employ the COIL as the kill mechanism to engage enemy targets in theater, providing a convincing argument that a FEL should be pursued for a ground-based missile defense network becomes even more challenging. The following list identifies trade-offs between the competing laser technologies for future ground-based applications:

1. Chemical Lasers: As highlighted earlier, these lasers have already been scaled to weapons grade power and also offer adequate beam quality and beam control. These laser beams operate at a wavelength of 3.9 microns for deuterium fluoride lasers to 1.315 microns for COIL lasers. Two critical limitations for the COIL are propagation in dense atmospheric environments and the toxic chemicals required for operation.⁹⁷ No matter how much energy a COIL system produces, this only exacerbates the effects of thermal blooming at surface levels. The net effect of employing the COIL on the airborne laser is to reduce the effects of atmospheric perturbations.
2. Solid-State Lasers: These are at a similar state of technical maturity as FELs but have distinct attributes and technical issues.⁹⁸ While the device does require cooling, there is not a significant radiation hazard as currently experienced in FEL systems.⁹⁹ However, a principal obstacle to scale a solid-state laser to weapons grade power is the removal of waste heat from the gain medium.¹⁰⁰ As the gain medium heats, optical quality is lost. Additionally, at weapons grade power levels, the projected size and complexity of solid-state lasers would far

exceed that of FEL systems.¹⁰¹ From this analysis, it does not appear that solid-state lasers are an attractive option for weapons grade applications and may function better for requirements below 100 kilowatts.

3. Free-electron Lasers: These have several distinct advantages for weapons-grade applications. Optimal beam quality, wavelength tunability, and future scalability to weapons grade power that can operate across a broad range of environments give the FEL a decisive advantage over conventional systems. Although the latest experiments with FEL technology have produced “halo effects,” just by the nature that FELs are wavelength tunable, makes the system optimal for ground-based missile defense employment.

This trade-off analysis between high energy laser systems supports the assessment that the FEL does have advantages over conventional lasers. This analysis does not however, address whether the FEL will meet system-level requirements for a viable missile defense platform once the technology is scaled to appropriate levels.

Optimal FEL Basing Network

FELs are anticipated to achieve weapons grade power levels within the next 10 years or sooner if the money is invested and the technology is pushed.¹⁰² Depending on successfully resolving the cornerstone issues of “haloing” and “heat dissipation” effects, fielding a network of ground-based FEL systems holds great promise.

An operational system could consist of 30 geographically dispersed FEL sites each strategically located along the perimeter of both the United States and Hawaii all controlled by five mission control centers. Each of these sites would be paired with optical high altitude airships to reduce atmospheric propagation effects and to extend the range of the ground-based

system. The airship represents the first iteration of technology required for developing space-based relay mirrors. The airships would enable the FELs to point their beams near the vertical thereby minimizing the paths of the beams through the more dense portions of the atmosphere.¹⁰³ The mobility of the relay stations would enable the FEL to propagate effectively through a dense atmospheric environment.¹⁰⁴

A critical advantage of fielding 30 FEL stations around the perimeter of the U.S., coupled with a corresponding number of high altitude airships, is to provide redundant operations. The following is an implementation example to further emphasize this point. Assume that 3.3 megawatt FELs are deployed along the perimeter of the U.S.¹⁰⁵ Assume that each FEL high altitude airship has a range of 500 nautical miles. The resultant effect is only 30 FEL sites, coupled with a corresponding number of high altitude airships, would be needed for missile defense. This would provide the U.S. with a network capable of engaging long and medium-range missile as well as short-range missiles possibly launched from the surfaces of naval vessels.

Depending on how the perimeters of Alaska, Hawaii and other U.S. territories are factored into the equation for “perimeter defense,” the U.S. perimeter could be estimated up towards 15,000 miles in length.¹⁰⁶ In the implementation example above, it is my estimate that the results of deploying 30 pairs of FELs and airships, would result in a total cost of around \$6 billion dollars in 2009 averages. Once a network of space-based relay mirrors are fielded, far fewer FEL ground stations would be needed. The appropriate number of sites in that scenario has yet to be determined.

At a level of 30 FELs and a corresponding number of relay mirrors, the complexity of the system could be very well managed.¹⁰⁷ Switching to autonomous mode, from standby, would only take a matter of seconds and having an operator in the decision chain would provide for weapons system surety. The system would always be online during times of crisis. Since the network would be ground-based, the system could run in autonomous mode for days on end without jeopardizing weapons system availability. The architecture would encompass a setup that would be easily accessible to maintenance personnel. Periodic tune-ups, calibrations, and re-fueling could be scheduled accordingly which would prolong the lifecycle of the weapon system.

CHAPTER 4 – SPACE-BASED RELAY MIRROR

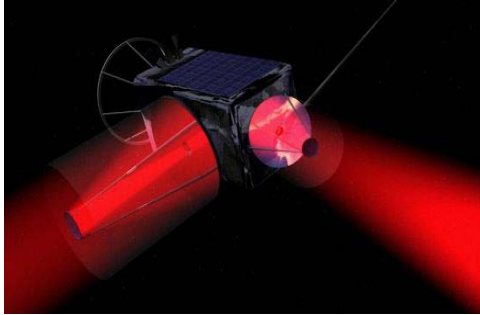


Figure 7 Courtesy of Air Force Research Lab

The Directed Energy office of the Air Force Research Laboratory at Kirtland Air Force Base, New Mexico, is in the initial stages of exploring system and technological designs to base a dual-mirror laser relay system in space.

The Aerospace Relay Mirror System (ARMS) is the prototype being used to further advance the technology for fielding this type of system. ARMS is a laser-relay system designed to focus and re-direct a laser beam from a ground-based laser source or airborne laser onto target, significantly increasing the laser's range and lethality.¹⁰⁸ Compared to a regular laser system, a redirected energy beam offers several advantages, including improved beam quality and the ability to hit beyond line-of-sight targets.¹⁰⁹ Relay systems could also improve adversary engagement timelines, while increasing the standoff range for manned system and serving as a relatively low-cost force multiplier for ground-based laser systems.

Low-earth orbit relay mirrors could be used to receive and transmit high-powered directed energy from one point on the earth to another, all at the speed of light. In a typical application, a laser beam would be directed from a ground-based system to a “receive mirror” on the relay system. That mirror would collect the beam, then pass it to a beam control system onboard the spacecraft, which would then re-condition the energy by way of advanced optics, then refocus and retransmit the laser to a target from a “transmit” mirror.¹¹⁰ This entire process would happen in near-instantaneous fashion, which is critical when targeting and engaging ballistic missile weapons which have a short burn time for powered flight.

Validating System Concept



Figure 8 Courtesy of Boeing Laboratory

Boeing Integrated Defense Systems and the United States Air Force recently made great strides in their relay system development program by successfully redirecting a laser beam to a target using the Aerospace Relay Mirror System.¹¹¹ The demonstration, which was conducted at

Kirtland Air Force Base, used a half-scale version of a relay-mirror payload that ultimately could be packaged and carried to high altitudes onboard an airship or as part of a space-based relay network.

System technicians fired a low-power, sub-kilowatt class ground laser from five kilometers away aimed at a 75-centimeter “receiving” mirror on the platform. The mirror then transmitted the energy to an onboard beam director and from there a “transmitting” mirror redirected the energy to a stationary target located three miles away, scoring a direct hit.¹¹² The success of this demonstration was a major step towards validating the technology and operational promise of the relay mirror system. Boeing plans to use the success of this experiment to further advance this technology and advance towards processing high energy laser beams.

The Air Force Research Laboratory (AFRL) plans on following Boeing’s vision by embarking on a plan that not only could a stationary relay system hit a stationary target, but could also be made deployable. This would ensure the system remains operationally viable.¹¹³ AFRL’s plan requires a system small enough to be carried on an airship that could relay and redirect high energy laser beams from laser platforms to destroy mortars, missile or other

targets.¹¹⁴ The test conducted back in 2006 only used low-energy laser power to demonstrate the concept.

Relay Mirror Advantages

A significant advantage of employing a space-based system is it enables each platform to operate autonomously in its own environment.¹¹⁵ The relay mirror would operate in space where there are no atmospheric disturbances to counter. The beam control system would receive energy that may have been affected by the dense atmosphere. The system would then cleanse the laser by way of adaptive optics and retransmit a beam of same or similar strength as the original through its “transmitter” mirror.

A second advantage of a space-based relay mirror is since the platform would be placed above the earth’s atmosphere, this would provide a global defense structure to hit any point on the earth either through direct line of sight targeting or through networking with other relay mirrors in orbit. This capability would represent a gigantic leap in missile defense technology as a practical application for moving laser energy beyond the horizon and beyond the limiting confines of the earth’s curvature.¹¹⁶

Pairing this system with a ground-based FEL offers the best option for developing a viable and credible network of missile defense systems. As stated earlier, FELs have the capability to operate at much shorter wavelengths over the more traditional lasers and if that system is developed to weapons grade output, would offer a unique advantages of penetrating the earth’s atmosphere without much reduction in beam quality.

Critical System Technological Challenges

There are several critical challenges that must be overcome before this technology can be considered a viable candidate for a global defense instrument. The challenges include space vehicle design, vibration and thermal management, attitude control, large angle skewing and momentum control of a multi-body system (two mirrors, optical bus, space bus).¹¹⁷ Space vehicle design must be small enough to send into orbit but have mirrors large enough to collect and re-direct high-energy beams.

In terms of optics, the relay mirror must be capable of precisely pointing, acquiring, tracking, and lasing targets. This operation will require line-of-sight maneuver capability for both mirrors.¹¹⁸ If line of sight cannot be maintained, the mirror must be sophisticated enough to re-direct the beam to another mirror that has line-of-sight lock on the target. Finally, large, lightweight mirrors must be developed as well as optical coatings and techniques for controlling jitter and optical aberrations.¹¹⁹ Currently mirrors that are able to receive and re-transmit high energy laser beams are still in the research and developmental stages. Developing mirrors that can handle high energy capacities at the multi-megawatt levels represents a significant challenge that must be overcome before this concept can move from research idea to design.

Notional Relay Mirror Constellation

Proposing a constellation of space-based relay mirrors to provide services to an infrastructure of ground-based free-electron laser systems is a matter of selecting an optimum number of satellites, their altitude and their configuration in some number of orbital planes. It is recommended that a constellation of 24 satellites at low-earth orbit be used to field a space-based relay mirror network. The satellites would be divided into six groups of four with each group

occupying a particular plane.¹²⁰ There would be six planes with all inclined 60 degrees to the equator and evenly spaced in each orbit.¹²¹

This constellation of mirrors in this particular orientation would ensure that each of the 30 FEL sites located around the perimeter of the U.S. would have instant access to one of the satellites at any time during a day. The mirror would then be able to engage a target within its operational footprint or network with another satellite to attack a target.

Each satellite in the constellation would contain an intelligence, surveillance and acquisition sensor to provide launch notification and tracking telemetry, and an automated internal system to lock onto a free-electron laser facility. Upon notification of a launch, the appropriate relay mirror would automatically slew to point the beam director at the coordinates provided by the acquisition sensor and begin “threat” tracking while the “receive” mirror would lock onto one of the laser ground stations to await energy.

A conus-based Mission Control Center would monitor the autonomous operation of the network. The FEL would autonomously fire its laser at the relay mirror. The relay mirror would then work autonomously to initiate an illumination, tracking, and firing sequence to hit and destroy the target. This process would happen in a matter of seconds so it would be imperative to have an operator in the decision-loop to cancel any firing commands in the event erroneous threat telemetry was received by the system. An end-to-end process of checks and balances would be an absolute must for deploying this network of space systems and ground sites. In the end, the relay mirror would re-direct the energy transmitted by a ground-based FEL to destroy an adversary’s ballistic missiles shortly after launch.

CHAPTER 5 -- CONCLUSION

The free-electron laser and space-based relay mirror could constitute the backbone of global U.S. ballistic missile defense network that would compliment a robust, multi-layered approach to missile defense. Such a network would be capable of protecting the U.S. homeland while also providing a capability to protect service members deployed in theater, as well as providing a blanket of protection to defend America's allies.

An unprecedented number of international actors have either acquired ballistic missile technologies or are seeking to acquire such technologies that could attack America's security at home and abroad. These actors include not only state, but terrorist organizations who are also interested in acquiring nuclear weapons or nuclear weapons-related technologies. North Korea has already been labeled as a nuclear-capable state and is now aggressively pursuing long-range missile technologies that could hold the U.S. and entire pacific region at great risk. Pyongyang announced they will be testing the Taepo-dong 2 missile within a few weeks which will validate Korea's growing long-range ballistic missile program.

The Republic of Iran recently conducted a rudimentary process to place a 60 pound satellite into low-earth space orbit. Although the country is far from being able to challenge America's interests in space, the fact that they were able to place a payload into orbit demonstrates Iran is on the verge of possessing a long-range missile capability. Additionally, Iran is projected to become nuclear capable by the year 2010. Coupled with the development of an intercontinental ballistic missile arsenal by the year 2015, Iran will be postured to attack America's borders with missiles carrying nuclear weapons or other weapons of mass destruction.

Given the dire nature of the growing threat environment, the missile defense system the U.S. should deploy must have a global-range capacity. This encompasses a defense network

capable of destroying a target within seconds after launch, which could also provide a much-needed deterrence structure as well. The ground-based missile defense system being deployed by the U.S. represents only part of the system that's required for global-range defense. In addition to being only a limited-mid-course defense system, the current network of kinetic energy interceptors cannot adequately discriminate against the growing sophistication of platforms possessed by U.S. adversaries.

Directed energy weapons systems may be able to transform the way America conducts ballistic missile defense operations. In the early 1990's, the U.S. had a rigorous space-based sensor and directed energy development program for the purposes of defending the homeland against missile attack. However, the program was eventually cancelled because the U.S. was not adhering to the restrictions as outlined in the Anti-Ballistic Missile Treaty which banned the development of missile defense programs. Now that the U.S. is no longer a signatory on this Treaty, a concerted effort should be made to revive directed energy technologies and create an interdiction capability through space. The most recent successes with the testing of the Air Force's airborne laser indicate research scientists have the technological know-how to scale directed energy beams to weapons grade power. Whether or not this platform is successful on the battlefield remains to be seen, and deployment of this platform to theater won't happen for another few years. However, once deployed and if successful, the laser could provide the blue-print for developing a ground-based system that could also use space as an enabling environment to interdict targets on a global scale.

The maturation of the free-electron laser and relay mirror technologies, offer tremendous potential for developing an extended-range missile defense network. The FEL has already demonstrated the capacity to successfully propagate the earth's dense atmospheric environment.

Tunability of the FEL's wavelength is a characteristic not possessed by conventional lasers. Although there is a lot of work that remains to overcome the "halo" and "waste dissipation" effects of the laser, the future of this technology being deployed as a missile defense system is very promising. The Navy has invested millions of dollars to design and fabricate a multi-megawatt FEL to defend against the growing range of cruise missile threats. The Navy plans on testing a weapons grade FEL within the next ten years or sooner if the technology matures faster.

In addition to the maturation of FEL technology, relay mirror technology has also matured and offer tremendous potential for being able to extend the range of ballistic missile defense systems in the not too distant future. The Aerospace Relay Mirror System is a dual-mirror prototype that's being used to advance and test demonstrate this technology. Although the Air Force has been successful in re-directing laser energy and scoring a direct hit against a stationary target, this test was conducted using a low-powered beam of energy. The Air Force is in the initial phases of designing optical mirrors that can receive and process weapons grade energy and re-direct that energy against a mobile platform. When relay mirror technology finally reaches maturation and is able to process weapons grade energy, the system could be coupled with a ground-based FEL of weapons grade power, to form a robust missile defense network. The future development of this technology is promising and offers a wide-range of missile defense applications and should be fielded as such.

APPENDIX

U. S. Air Force Directed Energy Response

CONOPS and Implementation Plan

This Directed Energy Response CONOPS serves as a template that can be used and formatted to serve as the conceptual framework for the Capabilities Review and Risk Assessment (CRRA) process once the directed energy technology matures and achieves weapons grade capability, and the political leadership desires to field a directed energy missile defense infrastructure. The CRRA is the U. S. Air Force process for evaluating capability requirements and revealing shortfalls, gaps and redundancies in the Air Force capability portfolio.¹²² The findings of the CRRA are incorporated into the Annual Planning and Programming Guidance (APPG) to provide senior leadership with operational, capabilities-based guidance for the Air Force Program Objective Memorandum decisions, and they are expressed in terms of the Joint Capability Areas in support of the Joint Capabilities Integration and Development System (JCIDS).¹²³ This Directed Energy Response CONOPS is developed to link the Air Force capabilities-based planning process to JCIDS, which will reflect the Air Force's institutional commitment to building a more lethal and better equipped joint force.

SECTION I – ISSUE

Problem Statement

Ballistic missile threats against the United States is a growing concern and presents one of the greatest challenges facing the continued security of our nation. An unprecedented number of international actors either have or are in the process of acquiring ballistic missiles capable of harming the U.S. Irrational actors are also seeking to cause harm to U.S. friends and allies around the world in hopes to influence public opinions about partnering with America. The

current U.S. ballistic missile defense infrastructure, although possibly effective against a limited number of missile threats, does not have the robustness, technological capacity nor the sophistication required to provide a truly global defense capability. Although there are plans to build and test a more responsive kinetic intercept technology for deployment within the next three years, this technology may continue to be ineffective against nations and non-state actors who possess weapons of great sophistication and capability to defeat planned missile defense shields.

Ongoing research and development with directed energy lasers, in particular, free electron lasers, and space-based relay mirrors could one day provide a global defense system aimed at defeating missiles during the initial stage of flight. Directed energy is a very attractive option since it operates at the speed-of-light, can be based within U.S. borders, and could be able to provide near instantaneous effects on a global realm against targets that continually threaten America. This technology, once it achieves weapons grade power, may one day enable the U.S. to credibly deter and effectively defeat ballistic threats originating from anywhere in the world.

Purpose of the Directed Energy Response CONOPS

Directed Energy Response CONOPS explains how U. S. Air Force capabilities can be used to destroy ballistic missile threats on a global scale using ground-based lasers strategically deployed within the continental U.S. This capability will continually support Joint Force Global Strike objectives, but will be used solely as a defensive countermeasure to destroy targets. A complimentary low-earth orbit network of relay mirrors may provide an over-the-horizon capability to attack key targets both globally and on short-notice. The ground-based system coupled with the space-based relay mirrors could provide a highly precise, near-instantaneous

long-range defensive response option even able to penetrate anti-access environments. Directed energy seeks to defeat adversary capabilities at their point of origin which will form the basis of a viable and credible missile defense capability to provide for U.S. security at home and abroad and a mechanism to protect friends and allies.

Relationship to Other U.S. Air Force CONOPS

This enabling CONOPS is in direct support of all U. S. Air Force CONOPS and presents a framework for directed energy response infrastructure. Other Air Force CONOPS include Global Mobility, Global Strike, C4ISR, Nuclear Response, Homeland Security, Global Persistent Attack and Agile Combat Support. These seven Air Force CONOPS are linked to national strategy, joint and Air Force doctrine, and the contributions of other agencies, alliances and coalitions through the Air Force Capstone Concept for Joint Operations.¹²⁴ These documents articulate how the Air Force will contribute to the Joint Force's ability to protect and advance U.S. national interests today and in the future, explain how we contribute to Joint Force operations, where we are going in terms of developing future capabilities, and how we will fight in the future.¹²⁵

SECTION II – OVERVIEW

Synopsis

Directed Energy Response is designed to create operational and strategic effects to defend the U.S. against missile attacks. This capability could also set the environment for joint forces to operate in, and defeat access challenges across, a broad spectrum of operational environments to include air, land, sea, space and cyberspace. Directed Energy Response will rely heavily on a synergistic coupling of ground-based systems with space-based low orbit satellites, all

commanded and controlled by a dedicated network of mission control centers. This enduring concept provides for around-the-clock threat assessment and immediate defeat mechanism directed against threatening missiles launched on a global scale. This response also provides a mechanism to defeat an adversary's theater ballistic missile systems, paving the way for freedom of maneuver for U.S., joint, coalition and multinational forces.

Previous U.S. strategies to address rising tensions and conflicts depended on U.S. forces having sufficient time to build up a coalition in theater. This approach requires a long logistics trail and a large amount of personnel resources during the early stages of conflict. Adversaries of the future will recognize this long deployment and basing phase and attempt to exploit this limitation through long-range, stand-off weapons. Both rising powers and non-state actors are acquiring or seeking to acquire ballistic missile systems to threaten or discourage the U.S. from operating in desired locations.

Need for Continued Military Transformation

The U.S. military is transforming to develop a more robust and lethal buffet of options to meet a radically changing national security environment. The U.S. must deal with a wide-array of challenges in theater and on the home front, and must continually be aware of a growing missile threat aimed at attacking our security and disrupting our way of life. The attacks of 9-11 help reemphasize that point.

Despite current advancements in directed energy technology, the U.S. faces four strategic challenges on the road ahead in creating a weapons grade high energy laser capability ... research and development, planning and programming, fielding and associated expenses. However, addressing each of these areas would be a prudent strategy as the U.S. moves toward

planning a multi-layered defense infrastructure. When current deterrence fails, the U.S. must possess a system capable of striking targets anywhere in the world, at a time of our choosing, and in a way to maintain persistent follow-on operations.

Desired Effects

Directed Energy Response offers two desired effects for a global ballistic missile defense capability:

- Multi-layered, complimentary missile defense infrastructure: Directed energy lasers complimented by space-based relay mirrors and combined with current and future kinetic-kill interceptors could enable the U.S. to defeat all missile threats regardless of location of origin and during any stage of flight.
- Near-instantaneous, long-range global stand-off response: Quickly neutralize and defeat an adversary's missile capability to defend the U.S. against global threats and to enable U.S. and coalition forces freedom of maneuver in theater.

Directed Energy Response must be able to provide a robust kill chain by striking targets within seconds of launch notification. Threats to the U.S. and forces deployed in theater may originate from anywhere on the globe in forms of intercontinental, medium-range, and short-range missiles, and will require an immediate kill response. When threats are identified and confirmed by joint force operators, the U.S. must respond immediately, regardless of the distance to target. Adversaries may use asymmetric offensive capabilities, such as chemical, biological, radiological, nuclear and high yield explosives onboard a wide-range of missiles. Directed Energy Response networks could defeat the WMD threat which will eliminate the requirement

for a large force build-up, or may be a part of an anti-access defeat mechanism to enable persistent attack joint operations.

SECTION III – CONTEXT

Time Horizon

This U. S. Air Force CONOPS addresses capabilities required to achieve desired effects 25 years from the present. This is a living document and will continually require updating as the directed energy technology continues to mature. Air Force doctrine and strategy must be developed in advance to correspond to projected domestic and international security environments, and as directed by political leadership.

Critical “Must-Haves” for System Development

Lessons learned as this technology matures dictate we pay attention to and push for the following critical “must-haves” to achieve desired system development:

- Congress fully resource and finance continued free-electron laser and space-based relay mirror research and development.
- Encourage cooperation between DoD and Department of Homeland Security (DHS) to promote R&D for this technology.
- Establish a common operational framework between services and research laboratories for system design.
- DHS conduct a National Needs Assessment to identify U.S. critical infrastructure vulnerable to ballistic missile attack.
- Eliminate Air Force and defense industry organizational and functional barriers that may slow system development and experimentation.

- U.S. establish bi-lateral technology sharing programs with allies to open dialogue about U.S. intentions and to determine what a future directed energy defense program would look like and how it could benefit them.

U.S. Air Force Advantages

The Air Force offers several advantages over other military services for leading the effort to further develop and field this capability:

- Well developed training and education system
- Dedication of our people from the most junior airman to the most senior officer.
- Strong sense of mission and performance expectations.
- Proven culture of exceeding standards in technology and achieving weapon system compliance.
- Ingrained desire to innovate and continually improve in technological development.

Critical Risk Factors and Potential Shortfalls

As the U. S. Air Force moves forward in further developing directed energy and relay mirror technology, there are a few risks and potential shortfalls that must be taken into account:

- Directed energy lasers may be unable to overcome atmospheric perturbations and technological limitations which will prevent employment as a viable weapons system.
- Inability of scientists to develop relay mirrors capable of receiving and redirecting the weapons grade energy required to be used as an effective defense mechanism.
- U.S. economy and financial constraints may prevent an aggressive approach to developing and validating this technology.

- Unintended geopolitical consequences that may sour relations between the U.S. and potential adversaries.
- Other countries, i.e. China, Russia and India may become the first to develop and field this technology.

SECTION IV – EMPLOYMENT CONCEPTS

Critical Capabilities

Directed Energy Response capabilities are those that directly enable the creation of desired operational effects in a multi-layered defense network. The critical capabilities listed below are required for successful employment of a directed energy system.

Space Superiority

Space superiority is the degree of dominance in space that enables free conduct of military operations and maneuver over land, sea and air at a given period of time to meet U.S. political objects and national military strategy. Space provides the ultimate domain from which to perform the breadth of global missile defense operations. Gaining and maintaining space superiority is a critical force enabler which includes satellite communications, positioning, navigation and timing, near real time threat detection, targeting data, damage assessment, and accurate and timely weather assessments and predictions.

Influence Operations

Influence Operations provide the ability to affect the perceptions and behaviors of states and non-state actors through the full range of offensive and defensive psychological operations, military deception, counterintelligence, counter-propaganda, public affairs and operations

security. IFO, as part of Information Operations, is governed by AFDD 2-5. As stated in the Global Strike CONOPS, *Influence operations capabilities are employed during peacetime to communicate national policy, resolve, political intent and project timely and accurate information to global leaders.* During directed energy response operations, influence operations would allow commanders to convey selected information and indicators to target audiences to deny, degrade and disrupt an adversary's decision processes to use weapons of mass destruction and the means to deliver them.

Enabling Capabilities

Enabling operational capabilities as stated in the Global Strike CONOPS are those capabilities that support or indirectly contribute to desired operational effects. Enabling capabilities for Directed Energy Response are *Command and Control, Surveillance and Reconnaissance, Intelligence, and Force Protection.*

Command and Control (C2)

The nature of Directed Energy Response requires a network of established and tested mission control centers manned by properly trained and experienced operators. C2 provides the capability to monitor and react to threat environments and command directed energy weapon systems to respond to any threatening missile attack. At its core, C2 is about decision-making and the individuals who make decisions; commanders and operators who process data in rapid fashion so that the weapons systems can provide near-instantaneous defeat options in defending the United States. Command and control capabilities must be flexible, enduring, versatile and adaptable to enable sufficient operator input at the joint force level.

Surveillance and Reconnaissance

As stated in the Global Strike CONOPS, Surveillance and Reconnaissance are the capabilities required to persistently and adaptively collect data to enable continuous characterization of all adversarial forces. Directed Energy Response operations require a robust global architecture provided by space-based relay mirrors capable of gathering information via onboard Intelligence SR sensors. This transformational objective set of capabilities and persistency would offer both wide area and focused collection of data. Sensors on space-based platforms must be highly observable and must be able to gather information inside of the adversary's threat environment. Joint and coalition forces would leverage the data collected in rapid reaction time and execute a directed energy response option and afterwards prepare other global strike assets to be used for follow-on operations. Terrestrial weather, space weather and other environmental sensor data must be accounted for and overcome with a wide-range of surveillance and reconnaissance capabilities located on other space-based platforms.

Intelligence

Intelligence is the product resulting from the collection, processing, integration, analysis, evaluation and interpretation of available information concerning foreign countries or areas. As stated in the Global Strike CONOPS, *intelligence capabilities provide information and knowledge about an adversary obtained through observation, investigation, analysis, and understanding*. As a result, the intelligence process enables the ability to produce the analytical products required to conduct Directed Energy Response operations. To support Directed Energy Response operations, data gathered by space-based relay mirrors need to be used to 1) create a database of potential threats, 2) perform detailed threat analysis, 3) anticipate potential military

application, and 4) build a true reflection of the threat environment and full-range of adversary capabilities. Directed Energy Response operations requires a common database to collect, store, share and exploit sensor information, and continuously forward actionable intelligence to the operators at the mission control centers.

Force Protection

Force Protection is vital to the operations at the mission control centers and ground-based directed energy laser networks. To minimize impact to operations and to ensure freedom of action, mission control centers and ground-based lasers must be secured from conventional and unconventional threats and payloads delivered by surface and air forces, terrorist activities, artillery, etc. Force protection includes the capability to detect and neutralize air threats (missiles as well as manned and unmanned aircraft), detection of CBRNE weapons and mitigation of effects, systems to warn forces of probable attack, and, if necessary, survive and operate under hostile conditions.

End State

The end state of a Directed Energy Response engagement would be upon completion of a successful intercept and destruction of a ballistic missile threat. In a theater attack scenario, the transition to capabilities addressed in the Global Persistent Attack CONOPS would occur when the Joint Force Commander determines the adversary's missile threat is diminished enough to allow persistent joint forces to operate freely and effectively.

SECTION V – SUMMARY

Directed Energy Response CONOPS represents the highest end and most challenging of the defense capabilities to plan, program and develop. The ability to defend the U.S., troops in theater, and our allies against tactical missiles filled with weapons of mass destruction represents the highest of priorities for battlefields of the future. If used to defeat ballistic missiles in theater, the Directed Energy Response option will enable the Joint Force Commander to employ a viable and credible system to destroy incoming missiles and create the conditions necessary to establish follow-on access for joint forces. If used to defeat strategic missile attacks against the U.S., the Directed Energy Response option will enable the President to direct a full-range of response options for follow-on joint force operations.

There is still a tremendous amount of research and development that needs to take place before bringing the directed energy technology to the forefront as a viable candidate for weapons system development. However, with the continued maturation of this technology and the growing threat of missile attacks and continued proliferation of weapons of mass destruction that will enable small-state or non-state actors to remain a credible threat, directed energy is a concept worthy of advancing and demonstrating in the not too distant future. This CONOPS serves as a guide to develop and potentially deploy a directed energy missile defense weapon system.

End Notes

¹ Way, Christopher R., Maria N. Zaitseva, Germ Proliferation: A Quantitative Analysis of the Spread of Biological Weapons, pg 2, April 2006, http://www.allacademic.com//meta/p_mla_apa_research_citation/1/3/9/8/7/pages139876/p139876-1.php

² Independent Working Group on Missile Defense, the Space Relationship and the Twenty-First Century, 2007, pg viii, <http://www.missilethreat.com/iwgreport>. The Independent Working Group on Missile Defense and Space Relationship was formed in 2002. Goals for the organization were: (1) to research the evolving missile threats to the United States and its allies; (2) to examine a transformation of the current missile defense infrastructure requirements; (3) to assess current and future missile defense opportunities in light of U.S. withdrawal from the missile defense for the United States.

³ President George Bush, Fact Sheet: Defending America and its Allies Against Ballistic Missile Attack, 2007, available at: <http://www.whitehouse.gov/news/releases/2007/10/20071023-5.html> During this speech to the National Defense University, President Bush explained the need for a Missile Defense System in Europe and discusses the progress defending America from ballistic missile attack.

⁴ Ibid, pg 1

⁵ Ibid, pg viii Rogue state is a phrase applied by some international theorists to states considered threatening to the world's peace. This means meeting certain criteria, such as being ruled by authoritarian regimes that severely restrict human rights, sponsor terrorism, and seek to proliferate weapons of mass destruction.

⁶ Unclassified Report to Congress on the Acquisition of Technology Relating to Weapons of Mass Destruction and Advanced Conventional Munitions, 1 January to 31 December 2006, pg 6, <http://www.fas.org/irp/threat/wmd-acq2006.pdf>

⁷ Ibid

⁸ Independent Working Group on Missile Defense, the Space Relationship and the Twenty-First Century, pg 3

⁹ Ibid, pg viii

¹⁰ Unclassified Report to Congress on the Acquisition of Technology Relating to Weapons of Mass Destruction and Advanced Conventional Munitions, pg 7

¹¹ Ibid, pg 7

¹² Ibid, pg viii

¹³ Independent Working Group on Missile Defense, the Space Relationship and the Twenty-First Century, pg 5

¹⁴ Ibid, pg viii

¹⁵ Independent Working Group, Missile Defense, the Space Relationship and the Twenty-First Century, January 2009, pg vi, available at: https://www.claremont.org/repository/docLib/200901291_iwg2009.pdf, this is an updated report to the January 2007 edition. Although the U.S. is making great strides to field the Airborne Laser in theater, there are currently no plans to deploy that platform stateside to protect the homeland against ballistic missile attack. The current kinetic kill interceptor vehicle network is of limited utility against a massive attack against the U.S. That system was designed only to counter a limited attack and limited missiles.

¹⁶ Ibid, pg viii

¹⁷ Ibid, pg viii

¹⁸ Ibid, pg viii

¹⁹ Ibid, pg viii

²⁰ Ibid, pg viii, Using space as a key operational enabler has the potential of raising the issue of weaponizing space which may alter the geopolitical landscape and create a race to weaponize space between the U.S. and strategic competitors.

²¹ Independent Working Group, Missile Defense, the Space Relationship and the Twenty-First Century, pg 6

²² Office of the Secretary of Defense, Annual Report to Congress, “The Military Power of the Peoples Republic of China” 2008, pg 2, available at:
[http://74.125.47.132/search?q=cache:GHyHuWvPpWIJ:hongkong.usconsulate.gov/uploads/images/pAw-](http://74.125.47.132/search?q=cache:GHyHuWvPpWIJ:hongkong.usconsulate.gov/uploads/images/pAw-Xhv1qHB7cBNrkQbc3A/uscn_others_2008030301.pdf+the+military+power+of+the+peoples+republic+of+china,+2008&hl=en&ct=clnk&cd=1&gl=us)

[Xhv1qHB7cBNrkQbc3A/uscn_others_2008030301.pdf+the+military+power+of+the+peoples+republic+of+china,+2008&hl=en&ct=clnk&cd=1&gl=us](http://74.125.47.132/search?q=cache:GHyHuWvPpWIJ:hongkong.usconsulate.gov/uploads/images/pAw-Xhv1qHB7cBNrkQbc3A/uscn_others_2008030301.pdf+the+military+power+of+the+peoples+republic+of+china,+2008&hl=en&ct=clnk&cd=1&gl=us)

²³ Independent Working Group, Missile Defense, the Space Relationship and the Twenty-First Century, Jan 2009, pg 6

²⁴ International Institute for Strategic Studies, “The Military Balance, 2008”, available at:
<http://www.iiss.org/> Dong-feng 3 and Dong-feng 21 constitute China’s intermediate-range ballistic missiles.

²⁵ Independent Working Group, Missile Defense, the Space Relationship and the Twenty-First Century, Jan 2009, pg 6

²⁶ Ibid

²⁷ Gertz, Bill, China Advances Missile Program, Washington Times, June 22, 2005

²⁸ Kahn, Joseph, Chinese General Threatens Use of A-Bomb if U.S. Intrudes, New York Times, July 15, 2005

²⁹ The Joint Operating Environment, 2008, <https://www.usjfc.com.mil/sits/j5/jsaldefault.apx>

³⁰ Ibid

³¹ Ibid

³² Independent Working Group, Missile Defense, the Space Relationship and the Twenty-First Century, Jan 2009, pg 3

³³ Ibid, pg 3 Iran possessed two elite military forces, the Artesh which is the standing military Army, and the Pasdaran which is a paramilitary organization. The Pasdaran serves as the regime’s principal point of contact for terrorist organizations like Hezbollah, Hamas, and Palestinian Islamic Jihad. Iran transferred the control of the Shahab-3 to the Pasdaran which signifies ballistic missile technologies could find their way into terrorist’s hands since Iran is a sponsor of terrorist activities.

³⁴ Hildreth, Steven A., “Iran’s Ballistic Missile Programs, an Overview,” CRS Report for Congress, July 21, 2008, available at: <http://www.fas.org/sgp/crs/nuke/RS22758.pdf>

³⁵ Independent Working Group, Missile Defense, the Space Relationship and the Twenty-First Century, Jan 2009, pg 3

³⁶ Ibid, pg 3

³⁷ Ibid, pg 4

-
- ³⁸ Bruno, Greg, International Institute for Strategic Studies, ““Council on Foreign Relations – Iran’s Nuclear Program,” July 18, 2008, pg 1, available at: <http://www.iiss.org/whats-new/iiss-in-the-press/july-2008/irans-nuclear-program.html>
- ³⁹ Ibid, pg 1
- ⁴⁰ Independent Working Group, Missile Defense, the Space Relationship and the Twenty-First Century, Jan 2009, pg 3
- ⁴¹ Ibid, pg 4
- ⁴² Ibid, pg 4
- ⁴³ Hafezi, Parisa, “Iran Reveals New Atomic Work, Draws Western Rebuke,” Reuters, April 8, 2008, available at: <http://www.reuters.com/article/newsMaps/IDUSHAF84321820080408.html>
- ⁴⁴ Ibid
- ⁴⁵ Jane’s Sentinel Country Security Assessments, “North Korea Armed Forces,” April 28, 2008
- ⁴⁶ Independent Working Group, Missile Defense, the Space Relationship and the Twenty-First Century, Jan 2009, pg 2
- ⁴⁷ Hildreth, Steven A. North Korean Ballistic Missile Threat to the United States, January 3, 2007, <http://www.64.233.169.132/search?q=cache:eviloq7FDw4J.html>
- ⁴⁸ Ibid
- ⁴⁹ Independent Working Group, Missile Defense, the Space Relationship and the Twenty-First Century, Jan 2009, pg 2
- ⁵⁰ Ibid, pg 2
- ⁵¹ Ibid, pg 2
- ⁵² Ibid, pg 2
- ⁵³ Beason, Doug, E., The E-Bomb, “The Promise of Directed Energy,” Da Capo Press, September 2005, pg 9
- ⁵⁴ Dr Kopp, Carlo, High Energy Laser Directed Energy Weapons, May 2008, pg 1, available at: <http://www.ausairpower.net/APA-DEW-HEL-Analysis.html>
- ⁵⁵ Kochemes, Alane, Andrew Gudel, The Heritage Foundation, “The Viability of Directed Energy Weapons,” April 28, 2006, available at: <http://74.125.47.132/search?q=cache:XbyMaPkyecwJ:www.heritage.org/research/ballisticmissiledefense/bg1931.cfm+directed+energy+weapons+laser&hl=en&ct=clnk&cd=17&gl=us>
- ⁵⁶ Spencer, Jack and Jay Carafano, PhD., The Heritage Foundation, “The Use of Directed Energy Weapons to Protect Critical Infrastructure,” August 2, 2004, pg 1, available at: <http://www.heritage.org/research/ballisticmissiledefense/bg1783.cfm>
- ⁵⁷ Ibid, pg 2
- ⁵⁸ Ibid, pg 2
- ⁵⁹ Ibid, pg 2
- ⁶⁰ Manning, Stephen, AP Business Writer, Wtop.com, “Pentagon Tests Missile Defense Shield Network,” December 6, 2008, available at: <http://www.military.com/news/article/pentagon-tests-missile-defense--shield.html?wh=news>
- ⁶¹ Zimet Elihu, Defense Horizons, “High-Energy Lasers: Technical, Operational, and Policy Issues”, October 2007, pg 1, available at: http://www.ndu.edu/inss/DefHor/DH18/DH_18.htm
- ⁶² Defense Daily, Sponsored By Boeing, Northrop Grumman, and Lockheed Martin, “Airborne Laser, Real Progress Toward Real Capability”, 2007, pg 1, available at: http://www.boeing.com/defense-space/military/abl/files/DD_Boeing.pdf

-
- ⁶³ Missile Defense Agency Fact Sheet, “The Airborne Laser,” June 2008, available at: <http://www.mda.mil/mdalink/pdf/laser.pdf>
- ⁶⁴ Missile Defense Agency Fact Sheet, “The Airborne Laser”
- ⁶⁵ Missile Defense Systems: The Airborne Laser, April 2007, available at: http://www.missilethreat.com/missiledefensesystems/id.8/system_detail.asp This site is dedicated to the promotion and understanding of directed energy technology.
- ⁶⁶ Ibid, pg 1
- ⁶⁷ Ibid, pg 1
- ⁶⁸ Worden, Simon, P. and Robert Luzzi, George C. Marshall Institute, “Why We Need the Airborne Laser”, pg 1 December 2003, available at: <http://74.125.113.132/search?q=cache:fXN-z7beb6gJ:www.marshall.org/article.php%3Fid%3D80+airborne+laser+planned+deployment&hl=en&ct=clnk&cd=6&gl=us>
- ⁶⁹ Ibid, pg 1
- ⁷⁰ In September 2008, the COIL was fired within the aircraft in a ground test, but the beam did not pass through the beam-steering unit but instead was passed to an onboard calorimeter.
- ⁷¹ Laser Focus World, “Airborne Laser Fires High-Energy Light Through Beam Steering System” pg 1, December 3, 2008, available at: http://www.laserfocusworld.com/display_article/346905/12/none/none/TECHN/Airborne-Laser-fires-high-energy-light-through-beam-steering-syste
- ⁷² Air Force Technology, “ABL YAL 1A, Airborne Laser USA”, July 2007, available at: <http://www.mindfully.org/Technology/2006/Airborne-Laser-ABL-YAL-1A2006.htm>
- ⁷³ Ellison, Rick, President of Missile Defense Alliance, Press Release, “Airborne Laser Capability One to Two Generations Ahead of the World, June 22, 2007, available at: http://www.missiledefenseadvocacy.org/news_pressrelease.aspx?news_id=429
- ⁷⁴ Ibid, pg 1
- ⁷⁵ Ibid, pg 1
- ⁷⁶ The Aegis Ballistic Missile Defense System is a network of sea-based defense systems designed to destroy short-range, intermediate range, and intercontinental ballistic missiles. There are 18 Aegis Ballistic Missile combatants in the U.S. Navy. Missile Defense Fact Sheet, “Aegis Ballistic Missile Defense”, available at: <http://www.mda.mil/mdaLink/pdf/aegis.pdf>
- ⁷⁷ Sofge, Erik, “Robotic Mirror Fleet May Boost Boeing’s Airborne Laser Accuracy”, October 6, 2008, available at: http://www.popularmechanics.com/technology/military_law/4286289.html
- ⁷⁸ Schactman, Noah, Danger Room, What’s Next in National Security, “Navy Pushing Laser “Holy Grail” to Weapons Grade”, March 26, 2008, pg 1, available at: <http://74.125.113.132/search?q=cache:ZQyniI2dWzGJ:blog.wired.com/defense/2008/03/battlefield-str.html+free+electron+laser+follow-on+to+airborne+laser&hl=en&ct=clnk&cd=4&gl=us> The Navy is pushing ahead with a 5-year, \$163 million dollar plan free electron laser energy up to weapons grade strength.
- ⁷⁹ Ibid, pg 1
- ⁸⁰ Ibid, pg 1
- ⁸¹ Coherence is the property of wave-like that enables the free-electron laser to exhibit interference. It is also the parameter that quantifies the quality of the interference which is also known as the degree of interference. Electromagnetic radiation is a self-propagating wave in space with electric and magnetic components. These components oscillate at right angles to each

other and to the direction of the propagation. NationMaster.com, Encyclopedia, "Free Electron Laser," available at: <http://www.nationmaster.com/encyclopedia/Free-electron-laser>

⁸² Ibid

⁸³ Ibid. Relativistic beams move at or near the speed of light.

⁸⁴ Jefferson Lab in the News

⁸⁵ Ibid

⁸⁶ Jefferson Lab, "Free Electron Laser"

⁸⁷ Scientific Assessment of High Power Free-Electron Laser Technology, "Introduction and Principle Findings," available at: <http://www.nap.edu/catalog/12484.html>

⁸⁸ Ibid, pg 1-1

⁸⁹ Jefferson Lab, "Free Electron Lasers"

⁹⁰ Orions Arm, Laser Weapons, "Categories of Laser Weapons", March 2007, pg 2, available at: http://74.125.113.132/search?q=cache:GefQ0JCCSgIJ:www.orionsarm.com/tech/Laser_weapons.html+free-electron+laser+wavelengths+penetrate+atmosphere&hl=en&ct=clnk&cd=6&gl=us

⁹¹ NASA, The Electromatic Spectrum, "The Infrared", pg 1, available at: <http://science.hq.nasa.gov/kids/imagers/ems/infrared.html>

⁹² Orions Arm, Laser Weapons

⁹³ Email with Col John Geis

⁹⁴ Ibid

⁹⁵ Ibid

⁹⁶ Ibid

⁹⁷ Even modest absorption through the atmosphere will lead to thermal blooming and will reduce the energy of light to the target. Scientific Assessment of High Power Free-Electron Laser Technology, pg 2-5

⁹⁸ Ibid, pg 2-5

⁹⁹ Ibid, pg 2-6

¹⁰⁰ Ibid, pg 2-6

¹⁰¹ Ibid, pg 2-6

¹⁰² Naval Institute Blog, "Perimeter Missile Defense," August 2006, available at: <http://www.militaryphotos.net/forums/showthread.php?t=133376>

¹⁰³ Ibid

¹⁰⁴ Ibid, pg 9

¹⁰⁵ Ibid

¹⁰⁶ Ibid

¹⁰⁷ Ibid

¹⁰⁸ Track, A. Lt Col, AFRL Completes Relay Mirror System Demonstration, <http://www.militaryphotos.net/forums/archive/index.htm>

¹⁰⁹ Ibid

¹¹⁰ United Air Force Fact Sheet, Relay Mirror Technology

¹¹¹ Boeing Demonstrates Aerospace Relay Mirror System, <http://www.boeing.com/ids/news/2006/q3/060807.htm>

¹¹² Ibid

¹¹³ Aerospace Relay Mirror System, available at: <http://seattlewebcrafters.com/nsecc/?q=node/view/54.htm>

¹¹⁴ Ibid

¹¹⁵ Ibid

¹¹⁶ United States Air Force Fact Sheet, Relay Mirror Technology, available at:
<http://www.kirtland.af.mil/shared/media/document/AFD-070404-044.pdf>

¹¹⁷ Ibid

¹¹⁸ Ibid

¹¹⁹ Ibid

¹²⁰ Space-Based Directed Energy Weapons, available at:
<http://74.125.45.132/search?q=cache:4pDgUTbhvFUJ.htm>

¹²¹ Ibid

¹²² Global Strike CONOPS, December 27, 2006. Document was gathered from the Air Force's Global Strike Office at the Pentagon and used as the basis for developing a Directed Energy Global Strike CONOPS. The information is unclassified and used strictly for research paper purposes. The CONOPS office was coordinated with to relay my intent and purposes of using the already Air Force approved Global Strike CONOPS as a source document.

¹²³ Ibid

¹²⁴ Ibid

¹²⁵ Ibid